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ACOUSTIC EVALUATION OF PNEUMATIC SOUND SOURCES FOR USE ABOARD SUBMARINES (U)

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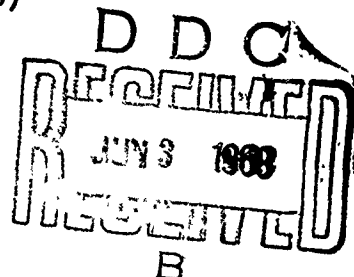
INTRODUCTION

The Naval Ordnance Laboratory was assigned the task of pro-
viding a high intensity sound source for use as an evaluation tool to
track submerged submarines operating in MILS arrays which are low
frequency narrow band detection systems. The source is to be used by
Commander Operational Test and Evaluation Force during the operational
phase Task III tests of the SUBROC weapon.

Pneumatic sources appear to be suitable for use aboard sub-
marines because they are reliable, capable of repetitive operation,
and are safe to operate. An experimental study was made to establish
the design characteristics of a pneumatic source which will operate
on a submarine at water depths of 500 feet or less and generate a
repetitive sound wave of 110 db re one μbar at one yard within the
frequency band of 5 to 50 cps.

Experimental Conditions

The acoustic measurements in shallow water were made at the
Patuxent River and the Chesapeake Bay in water depths of 110 to 156
feet. The acoustic measurements in deep water were made at sea off
the coast of Fort Lauderdale, Florida in water depths of 600 to 1000
feet. The receiving system used consisted of two or more piezo-
electric hydrophones coupled by appropriate electronic circuitry to a
multichannel magnetic tape recorder. The response of the system was
flat from 5 to 5,000 cps., being limited at the lower end by the time
constant formed by the hydrophone capacitance and the input impedance
of the cathode follower used to couple the hydrophone to the tape
recorder, and at the higher end by the frequency-modulated reproduce
electronics of the magnetic tape recorder. Filtering of the signals
in the 5-50 cps band was accomplished by passing the recorded signals
through an electronic low-pass filter. For all measurements the

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hydrophones were oriented in the horizontal plane with the source at distances of six inches to twelve feet from the origin of the sound source.

For the tests in the MILS array, a pneumatic source was suspended from the the USS SALINAN and operated at depths of 30 to 500 feet in the center of the array. The source was installed on the USS SEA ROBIN (SS 407) and operated at depths of 57 to 400 feet with the submarine running at speeds of 5 to 12 knots. The acoustic signals which were detected by the MILS hydrophones were recorded on magnetic tape and direct-writing recorders at the Grand Turk shore facility.

DESCRIPTION OF PNEUMATIC SOURCES

All pneumatic sound sources operate on the same principal, i.e. a volume of compressed air is released instantaneously to form an air bubble which oscillates and radiates acoustical pressure waves in the water. The principle differences between types of pneumatic sources are the mechanical techniques used to seal the moving parts, ratio of chamber openings to chamber diameters, methods used to release the compressed air, and the methods used to control the operation of the sources. Table 1 presents the mechanical characteristics of ten pneumatic sources which were evaluated in this study. The chamber volumes varied from 3 cu. ins to 436 cu. ins. The sources were constructed of mild steel, stainless steel, aluminum, and aluminum alloys. Lapped metal joints, rubber O-rings, teflon O-rings, and flat polyurethane seals were used to seal the main chambers. The operating chamber pressures varied from 200 psi to 2500 psi. Electric solenoids and threshold triggering were used to initiate the sources.

Photographs of two basic types are shown on Figure 1. The NOL sound source WOX-1 is shown on the left and the BOLT ASSOCIATES Pneumatic Acoustical Repeater (PAR Model P-300) is shown on the right. The WOX-1 source and a smaller version, the WOX-2, have the same configuration and operate according to the same principles. They differ only in size. WOX-1 has a main chamber volume of 400 cubic inches and WOX-2 has a main chamber volume of 5.7 cubic inches. Figure 2 is a sketch that applies to either source. The principle of operation is as follows. Compressed air from the supply entering chamber B drives the piston upward. First, the exhaust ports slide past teflon O-ring E_2 to seal bottom end of main chamber A. Then teflon O-ring E_1 slides past equalizing ports to seal access between chambers A and C. The piston continues to move slowly as air trapped in chamber C leaks out through the relief valve. Toward the end of the stroke, Ports D_1 and D_2 slide over teflon O-rings E_3. Air then flows into chamber A through chamber B until both chambers reach the supply pressure. The source is fired by opening the solenoid valve

and admitting air into chamber C. The piston begins to move downward until the O-ring E_1 slides past the equalizing ports. The pressure in chamber C rapidly becomes equal to that in chamber A and the piston is driven out with an initial force of

$$F_o = (P_A - P_H) \times (\text{cross-sectional area of piston})$$

where P_H is hydrostatic pressure and P_A is the pressure in chamber A. For the WOX-1 the cross-sectional area of the Piston is 50 square inches, hence, for $(P_A - P_H) = 1000$ psi,

$F_o = 5000$ pounds. Such forces cause the piston to undergo extremely high accelerations. The relative positions of O-rings E_1 and E_2 are such that the piston travels for a short distance with equalizing ports open so that when the exhaust ports slide past O-ring E_2 they do so with a high velocity and air is expelled rapidly to form an oscillating bubble. As the piston moves downward, O-ring E_3 passes over the Ports D_1 and D_2 and air is trapped in chamber B. The potential energy stored in compressing this air serves to restore the piston to the filling position. Both sources will operate at main chamber pressures of 100 to 2000 psi.

A simplified sketch of the BOLT ASSOCIATES Pneumatic Acoustical Repeater (PAR) is shown on Figure 3. The type 1 has a volume of 3 cubic inches and the Model P-300 has a volume of 121 cubic inches. Both models operate according to the same principles. The cycle of operation of the PAR starts with the opening of the return solenoid which allows compressed air to fill chamber B. The shuttle is driven upward and presses on the front and rear polyurethane seals simultaneously to form two closed chambers A and C. The air in chamber B bleeds down to a pressure determined by the relief valve. The fill solenoid is opened to fill chamber A. The sealing diameter at the upper end of the shuttle is slightly greater than that of the lower end. As the pressure in chamber A increases, the net force tending to close the shuttle increases. The PAR is fired by opening the trigger solenoid valve which allows air to enter chamber C until the pressure in chamber C is equal to that in chamber A. At that time the only forces acting to keep the shuttle up are the forces due to the pressure in chamber B and the hydrostatic pressure acting on the bottom of the shuttle. If the pressure in chamber A is larger than hydrostatic, the shuttle will be forced downward rapidly allowing the air to escape through the exhaust ports. Compressed air trapped in chamber B returns the shuttle immediately after chamber A has been exhausted. The cycle may then be repeated. A relief valve set at 5 psi, relieves pressure behind the top seal. A third relief valve, set at 5 psi, relieves the fire chamber (C) on top of the shuttle of

any pressure until the fire valve is opened.

EXPERIMENTAL RESULTS

The results of the study are based on approximately 1000 shots which were made over a period of one year. The results that follow are discussed in connection with the appropriate parameter. Source levels are given in decibels referred to one μbar at one yard. Here the term source level is the ratio, expressed in db, of the largest peak-to-peak sound pressure produced by the oscillation of the bubble to the peak-to-peak value of the commonly accepted reference standard of one root-mean-square microbar (dyne per square centimeter). The source level is computed by measuring from the largest positive to the largest negative peak, dividing by the peak-to-peak sound pressure of one rms microbar (2.83 microbars), and expressing this ration in db.

Sound Field

Representative recording of the acoustic pressure versus time for the pneumatic sound WOX-1 and the PAR are shown in Figures 4 and 5. The curves indicate that the initial pressure rises to a peak value within 0.5 to 1.0 millisecond as the airbubble is ejected from the chamber. As the bubble expands and contracts the acoustic pressure in the water goes below hydrostatic, rises above hydrostatic, decays below hydrostatic, etc. until all of the energy is dissipated. As the depth increases the bubble oscillations produce an acoustic pulse which approaches a damped sinusoidal wave. Curves of peak source level versus depth are shown on Figure 6 for several types of sources. The NOL pneumatic sound source WOX-1 and the BOLT PAR, Model P-300, operated satisfactorily within the depth range of 33 to 500 feet at chamber pressures of 1000 to 2000 psi. With the exception of the Lamont Geological Observatory source Mk 4 the performance of the remaining sources at depths in excess of 100 feet was poor. The peak acoustic level of the WOX-1 was 124 db and this level decreased to a value of 122 db at a depth of 500 feet (chamber pressure of 2000 psi). The peak acoustic level of the PAR (Model P-300) was 115 db at a depth of 500 feet and chamber pressure of 1000 psi. At this pressure and depth the peak acoustic level of the WOX-1 was 117 db.

Fundamental Frequency of Acoustic Signatures

The fundamental frequency of the initial pulse of an oscillating bubble, neglecting the action of gravity, may be expressed by the following theoretical equation:

$$f_o = 27.7 \frac{(d + 33)^{5/6}}{(P_c V_c)^{1/3}}$$

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where f_o is fundamental frequency of the initial pulse, d is source depth in feet, P_c is chamber pressure in pounds per square inch and V_c is the chamber volume in cubic inches.[1]

Curves of fundamental frequency versus source depth are presented in Figure 7 for several pneumatic sources operated at pressures of 1000 and 2000 psi. The data indicate that the fundamental frequency of the pulse emitted by a pneumatic source may be expressed by the relation:

$$f_o = (K) \frac{(27.7) \ (d + 33)^{5/6}}{(P_c \ V_c)^{1/3}}$$

where K is a constant, which is dependent upon the design
characteristics of the source

Correlation of the field data with theoretical data on the frequency versus volume for several depths and pressures indicate that the fundamental frequency of an ideal source operated at a depth of 500 feet and chamber pressure of 2000 psi varies from 285 to 52 cps as the volume is varied from 3 to 500 cubic inches.

Effect of Varying Chamber Pressure and Volume at Constant Depth

The effect of varying chamber pressure is shown on Figure 8. The source level is plotted as a function of chamber pressure for five sources of different size operated at a depth of 66 feet. The source level of the BOLT PAR (Volume - 3 cubic inches) and the Lamont source Mk 2 increases by 3 db when the chamber pressure is doubled. The source level of the large sources (chamber volume - 200 cubic inches) increases by 4 to 6 db as the chamber pressure is doubled. At a chamber pressure of 2000 psi, the source level of the BOLT PAR increases by approximately 10 db when the chamber volume is increased by a factor of 40.

Efficiency of Pneumatic Sources

Values of relative efficiency of several sources are listed in Table 2 for various depths and chamber pressures. The data indicate that the efficiency of each source decreases as the depth increases when the chamber pressure is constant. For example the BOLT PAR (Volume 121 inches) has an efficiency of 9.6 % at a depth of 50 feet and a chamber pressure of 2000 psi. The efficiency of this source is 4.0% at a depth of 500 feet. When the depth is constant the efficiency increases as the pressure increases within the

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operating pressure range of the source. The Lamont source Mk 4 has an efficiency of 12.0% at a depth of 132 feet and a chamber pressure of 2000 psi. This is the most efficient source tested at depths in excess of 100 feet.

Table 2   Relative Efficiency of Pneumatic Sources

Source	Chamber Volume (in^3)	Chamber Pressure (psi)	Source Depth (ft)	Efficiency (percent)
BOLT PAR	3	1000	33	17
		500	200	4.0
		1000	200	4.4
		2000	200	5.0
BOLT PAR	121	500	50	6.0
Model P-300		1000	50	9.3
		2000	50	9.6
		1000	200	6.5
		2000	200	7.0
		2000	500	4.0
LAMONT MK 4	22	2000	132	12.0
WOX-1	400	1000	200	3.7
		2000	500	3.7
WOX-2	5.7	2000	20	10.6

Source Level Content of Pneumatic Sources in 5 - 50 cps band

A typical narrow-band detection system is the Grand Turk MILS array which contains six hydrophones in a pentagon at a depth of approximately 2800 fathoms. The outside diameter of the array is 40 nautical miles. Figure 9 is a plot of the terminal sensitivity of the system. Hydrophone 101 (unit 1), which is connected to 182 miles of cable, cuts off all frequencies above 150 cps. The response of this unit falls off at the rate of about 18 db per octave at frequencies above 75 cps. The response of hydrophone 106 (unit 6), which has the highest frequency response falls off at the rate of 25 db per octave at frequencies above 300 cps. The accurate computation of an acoustic fix on sound created by an underwater source requires comparison of arrival times for direct transmission paths on at least three hydrophones. The maximum horizontal range possible for a direct sound transmission path is limited to about 17 miles from a hydrophone. For reliable detection by the hydrophones, a sound source in the center of the array should have a source level of 100 to 110 db in the frequency band of 5 to 50 cps.

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In order to simulate the response of the MILS system, pressure-time curves of several sources were played back through an SKL filter set for a pass band of 5 to 50 cps. The source levels of the resulting waves were computed according to the procedure described previously. The BCLT PAR (Volume 121 cubic inches) and the NOL WOX-1 (Volume 436 and 400 cubic inches) were the two types which were operable at depths of 33 to 500 feet and the source level content in the 5 to 50 cps band of these sources is plotted versus depth for chamber pressures of 1000 and 2000 psi in Figure 10. These data indicate that for a given desired source level in the 5 to 50 cps band, the principal advantage of a large chamber volume is that the source may be operated at lower pressures at the deep depths without decreasing the source level appreciably. The WOX-1 source will produce a source level of 110 db in the 5 to 50 cps band at a depth of 500 feet, when operated at a chamber pressure of approximately 1000 psi, whereas, the PAR, Model P-300, must be operated at a chamber pressure of 2500 psi to produce this level.

Characteristics of PAR Signals in MILS Array

For the tests of the PAR in the MILS Array no attempt was made to obtain a quantitative measure of the sound level at the MILS hydrophones. Observers at the Grand Turk Facility recorded the arrival times for direct transmission paths on all hydrophones which detected the PAR signals. The signals were easily identified on three or more hydrophones for all shots at ranges of 17 miles or less.[2] The locations of all the shots were computed from the arrival times of the signals received on three or more hydrophones. The relative intensity of the PAR signals as a function of depth, range, and chamber pressure is presented on Figure 11. The relative intensity is expressed in decibels which is the difference in maximum amplitude of the incoming signal and the minimum noise level on the record. These data confirm the results of the free-field measurements, which indicate that the PAR signal strength in the 5 to 50 cps band decreases as the depth increases from 200 to 500 feet.

CONCLUSIONS

The results of this study show that the PAR and the pneumatic source WOX-1 will operate consistently at water depths of 500 feet or less and generate a repetitive sound wave of amplitude of 110 db within the frequency band of 5 to 50 cps. The PAR is satisfactory for use in tracking submerged submarines in arrays which require a high intensity low frequency source.

The results indicate that the source level and frequency content of a pneumatic source can be varied over a wide range by varying the air volume and pressure.

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Pneumatic sound sources are less efficient than conventional magnetostrictive and piezo-electric transducers are for generating underwater sound waves. The acoustic efficiency of pneumatic sound sources decrease as depth is increased if the chamber pressure and volume remain constant and increase with increasing chamber pressure if the depth and volume remain constant.

It is concluded that pneumatic sources are simpler and superior to conventional transducers when used aboard a submarine to generate repetitive low frequency sound waves of high intensity.

[1] G. M. Davidson and J. W. Brooks, "Acoustical Characteristics of Pneumatic Underwater Sound Sources," (U) U.S. Naval Ordnance Laboratory Technical Report 64-51 (Conf) July 1964

[2] Jean Scoggin, "Acoustic Tests of PAR and SUBROC Water Entry," (U) U. S. Naval Ordnance Laboratory Technical Report 64-123 (Conf) July 1964

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Table 1 Mechanical Characteristics of Pneumatic Sources

Source Type	Chamber Volume (in³)	Type Seal	Weight (lbs)	No. of Air Inlets	Operating Pressure Range (psi)	Maximum Test Depth (ft)	Constructed of	Method of Initiation
LAMONT MK 1	200	Steel joint	100	1.0	500 to 2000	200	Steel 1020	Elec. Solenoid
LAMONT MK 2	44	Steel joint	100	1.0	500 to 2000	150	Steel 1020	Elec. Solenoid
LAMONT MK 3	350	Rubber O-ring	150	1.0	200 to 500	200	Steel 1020	Elec. Solenoid
LAMONT MK 4	22	Teflon O-ring	50	1.0	500 to 2000	132	Aluminum Alloy 6062	Threshold Triggering
BOLT PAR Type 1	3	Polyurethane ring	15	3.0	500 to 2000	268	Stainless Steel 303	Elec. Solenoid
BOLT PAR Model P-300	121	Polyurethane ring	200	3.0	500 to 2500	550	Stainless Steel 303	Elec. Solenoid
NOL WOX-0	400	Steel joint	250	1.0	500 to 1000	400	Steel 1020	Elec. Solenoid
NOL Pneumatic Chamber	168	Rubber O-ring	30	1.0	500 to 2000	500	Steel 1020	Threshold Triggering
NOL WOX-1*	400 and 436	Teflon O-ring	270	2.0	200 to 2000	500	Stainless Steel 303	Elec. Solenoid or Threshold Triggering
NOL WOX-2	5.7	Rubber O-ring	15	2.0	200 to 2000	66	Stainless Steel	Elec. Solenoid or Threshold Triggering

*Volume is dependent upon type piston used.
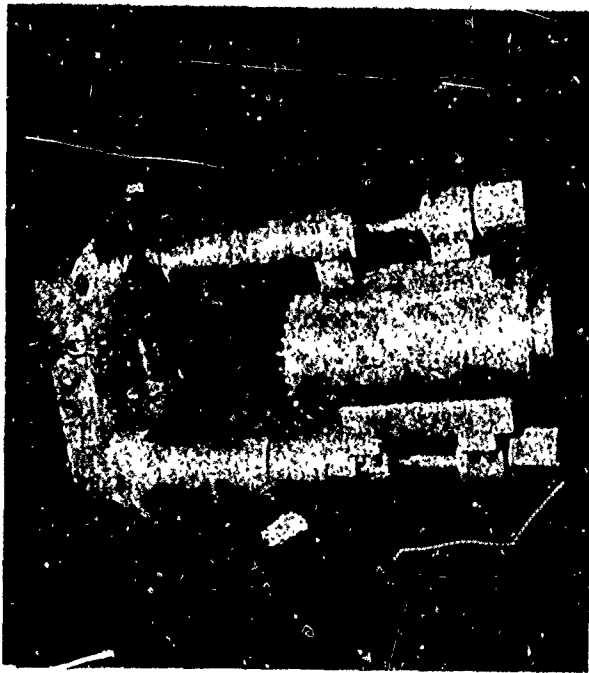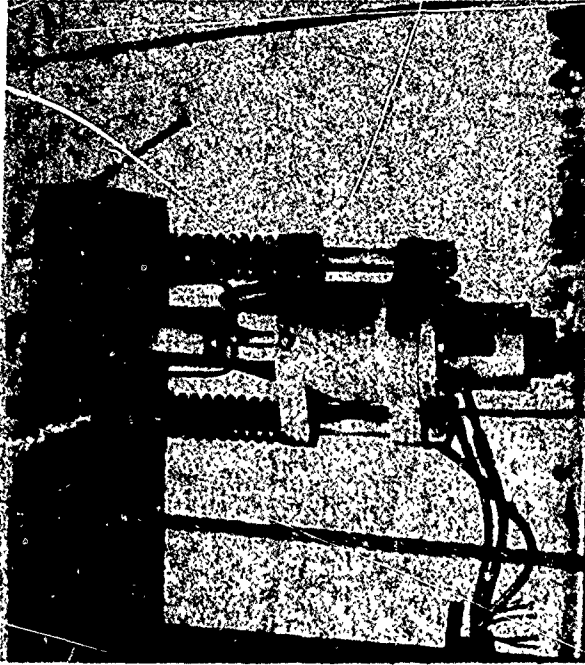
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BOLT ASSOCIATES PNEUMATIC
ACOUSTICAL REPEATER (PAR)

NOL PNEUMATIC SOUND SOURCE WOX-I

FiG. I   Pneumatic sound sources
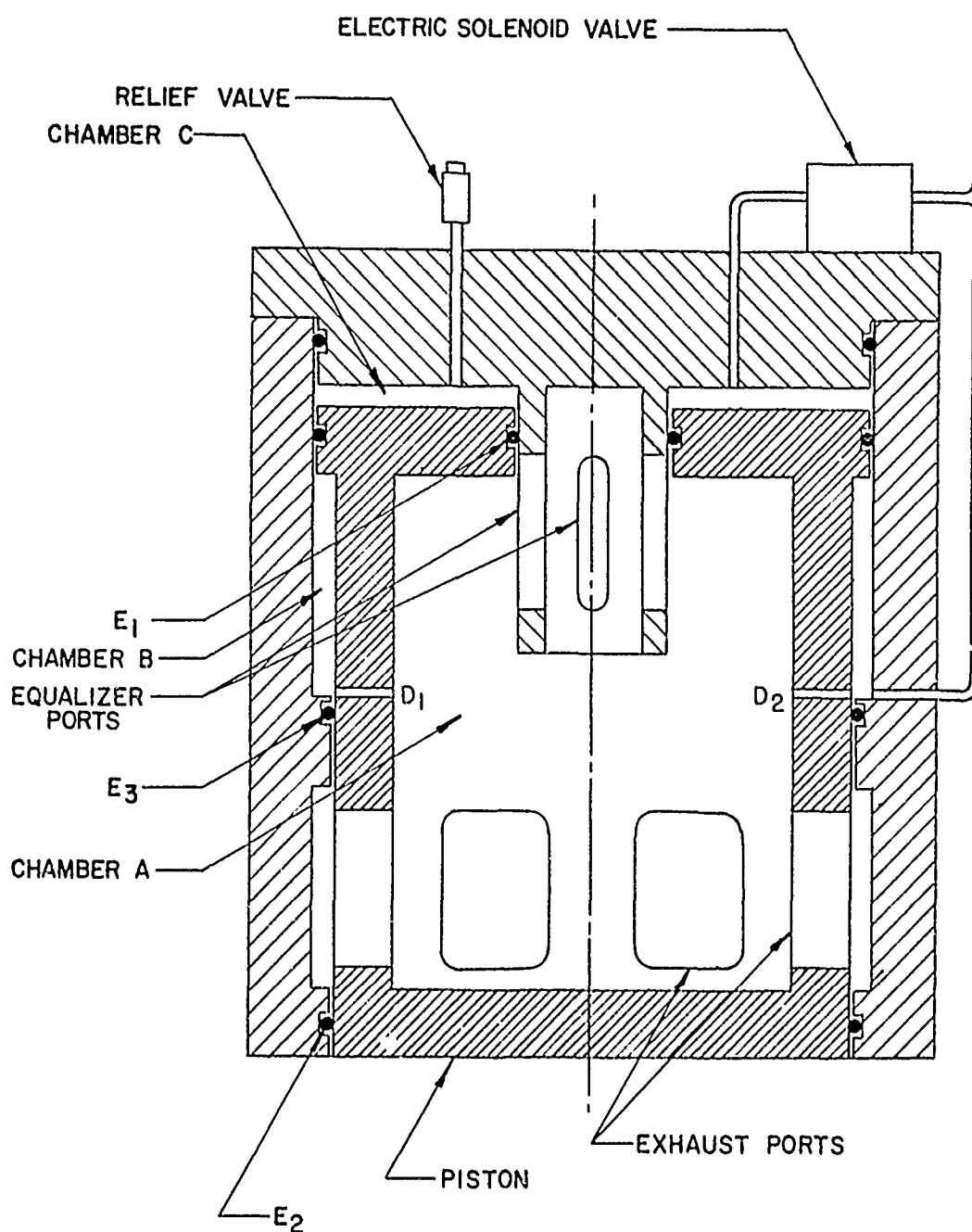
FIG. 2. NOL pneumatic sound source WOX-1 and 2.

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SUPPLY IN

RETURN SOLENOID VALVE

TRIGGER SELENOID VALVE

FILL SOLENOID VALVE

UPPER HOUSING

REAR SEAL

C

SHUTTLE

B   A

FRONT SEAL

RETURN SHAFT

EXHAUST PORTS

LOWER HOUSING

RELIEF VALVE
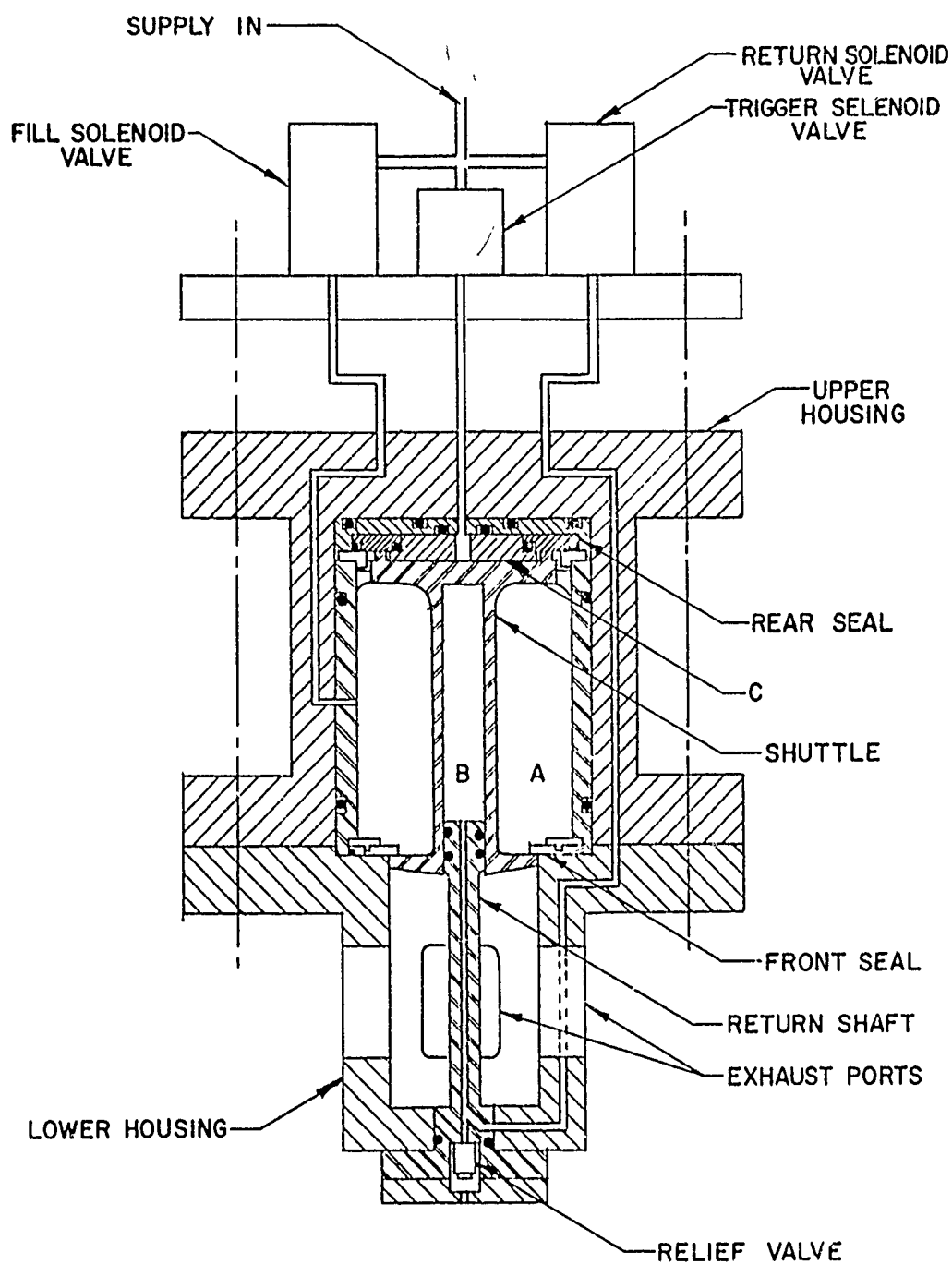
FIG. 3. Bolt Associates pneumatic acoustical repeater.
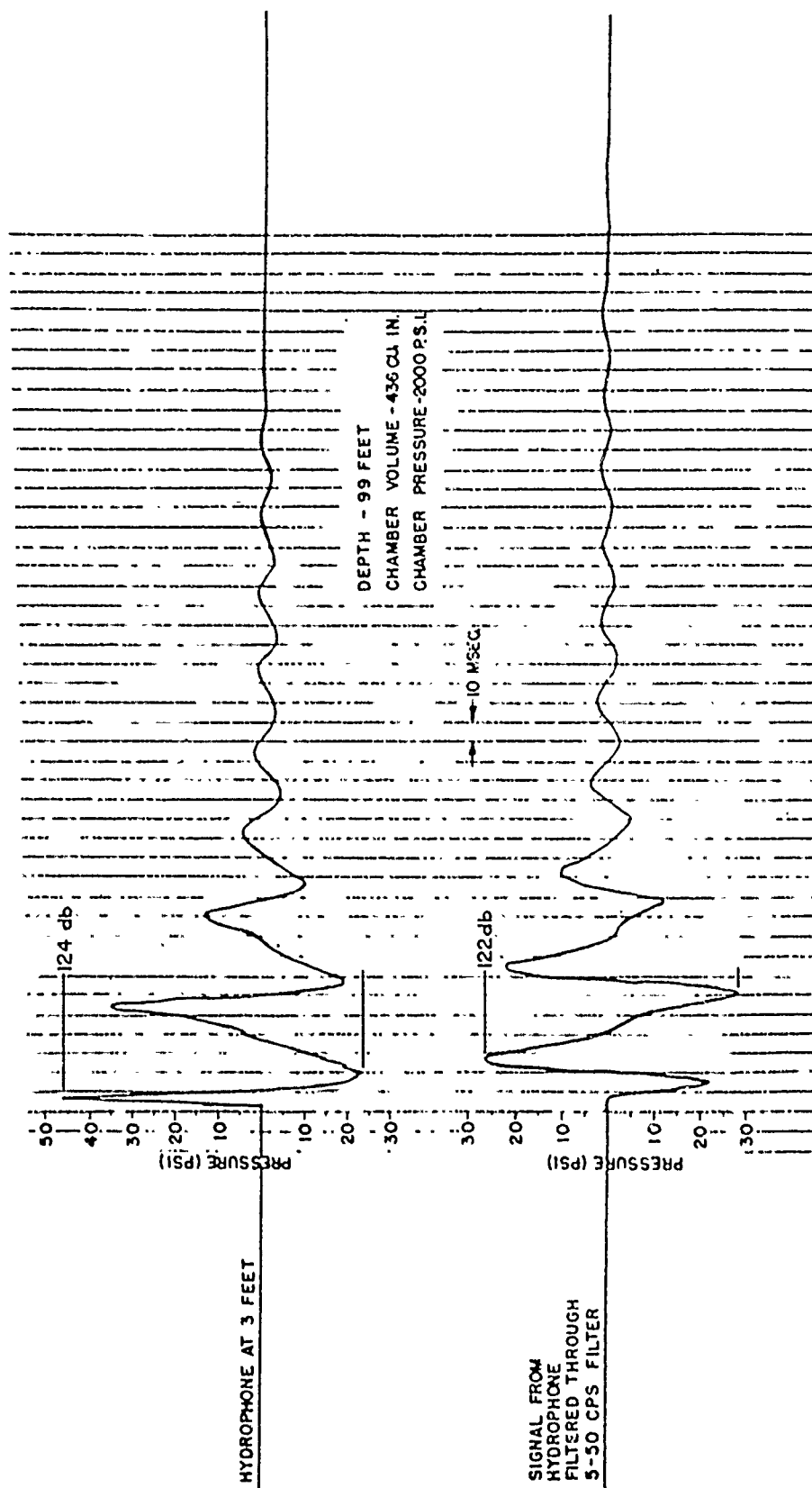
Fig. 4.   Acoustic signature of pneumatic sound source WOX-1.
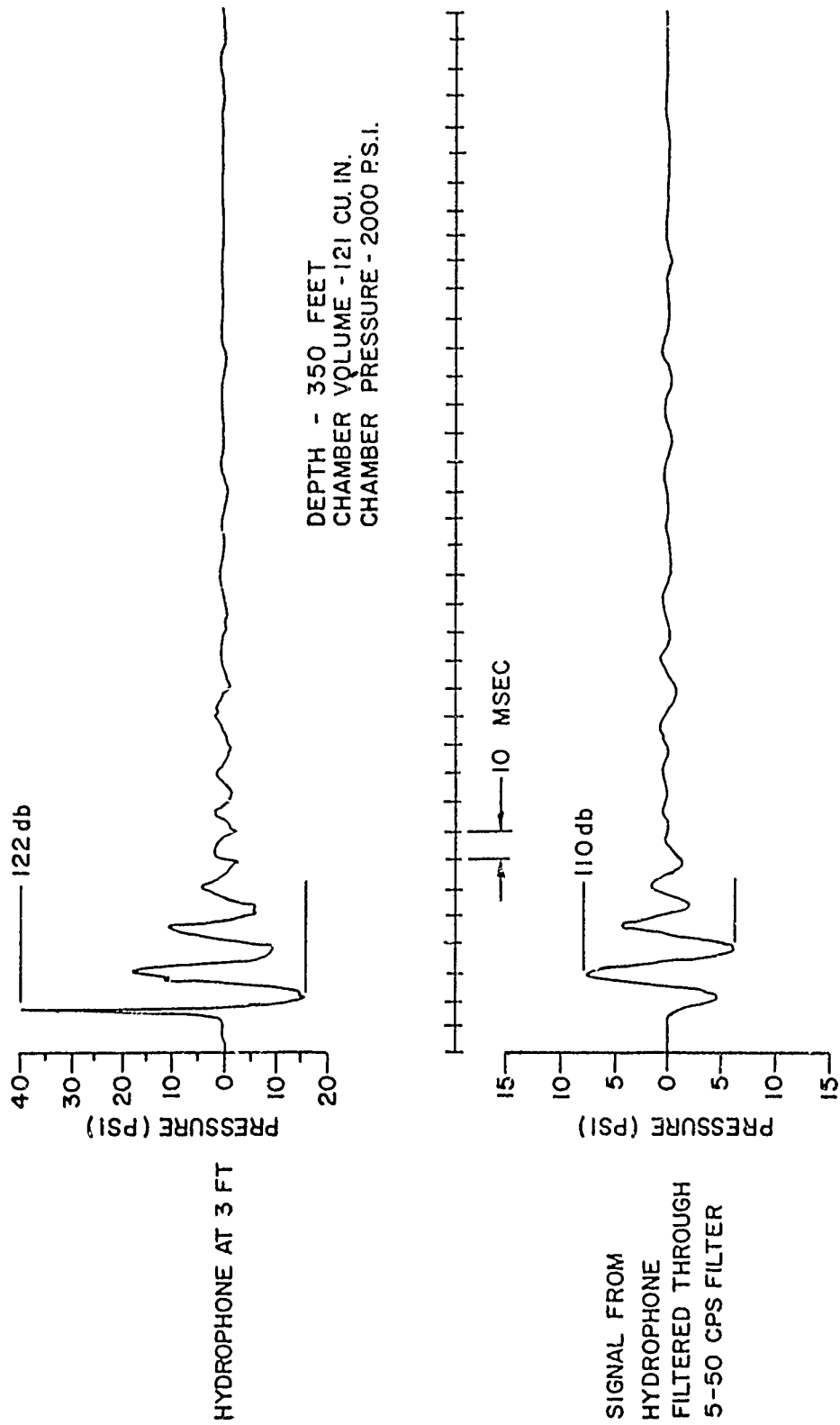
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Fig. 5. Acoustic signature of pneumatic acoustical repeater.
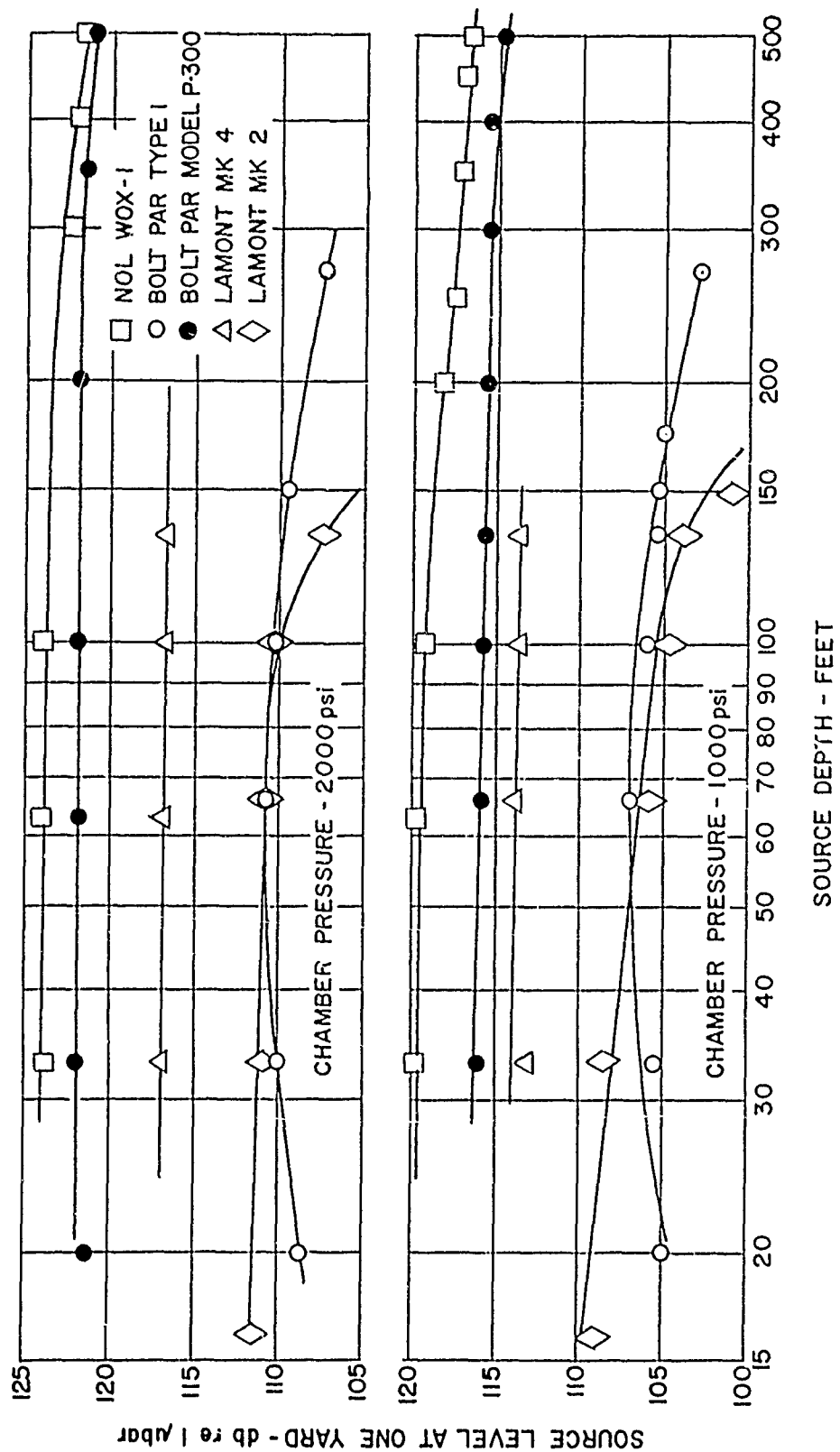
Fig. 6. Source level of pneumatic sources vs depth.
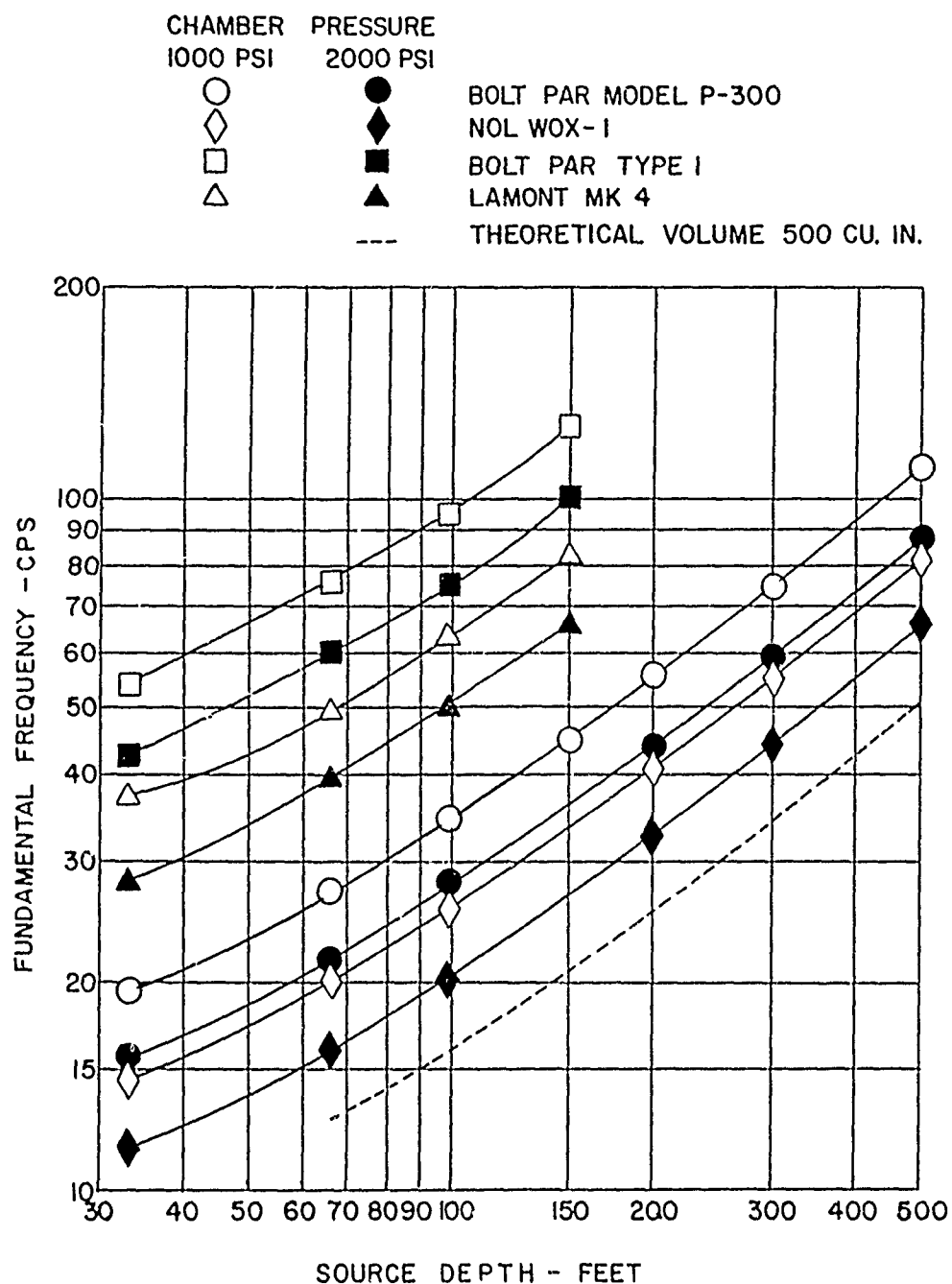
FIG. 7. Fundamental frequency of pneumatic sources vs depth.

DEPTH = 66 FEET
○ VOLUME = 200 CU. IN. LAMONT MK I
□ VOLUME = 44.5 CU. IN. LAMONT MK 2
△ VOLUME = 3.0 CU. IN. BOLT PAR
△ VOLUME = 121 CU. IN BOLT PAR MODEL P-300
● VOLUME = 400 CU. IN. NOL

CHAMBER PRESSURE - P.S.I.

SOURCE LEVEL AT ONE YARD - db re 1 μbar
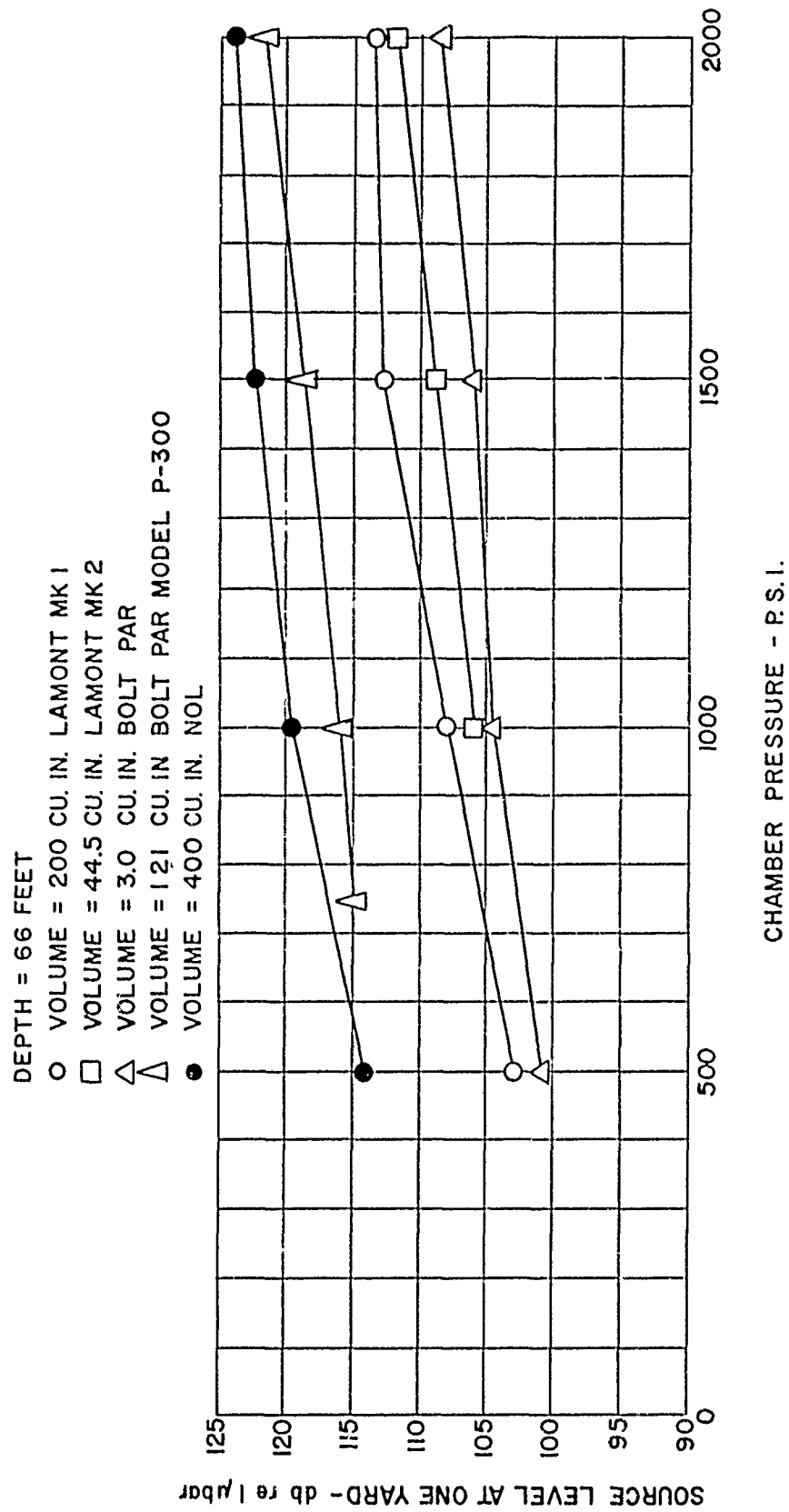
FIG. 8. Effect of varying chamber pressure at constant depth.
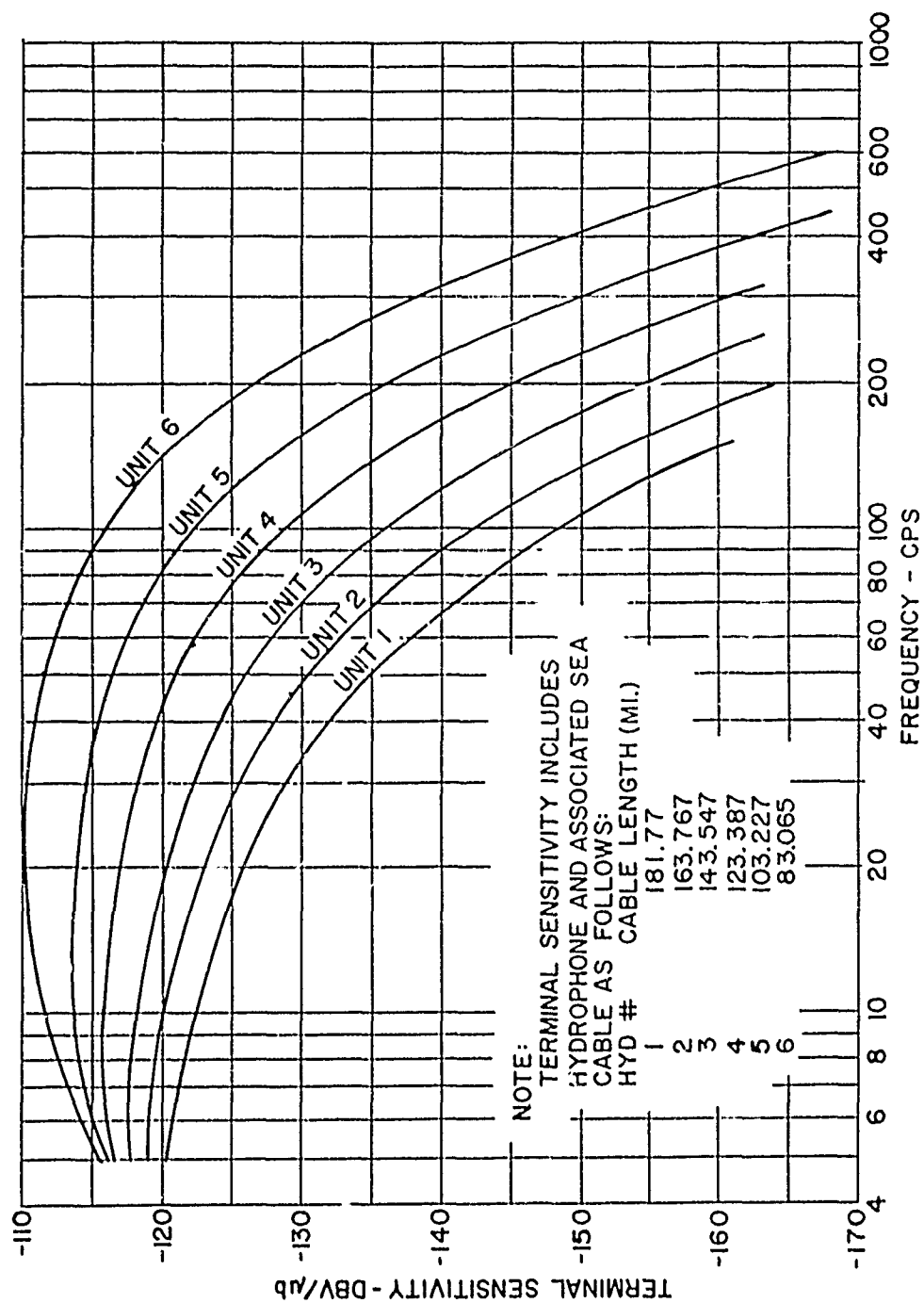
FIG. 9. Terminal sensitivity of turks pentagon units.

NOTE:
TERMINAL SENSITIVITY INCLUDES
HYDROPHONE AND ASSOCIATED SEA
CABLE AS FOLLOWS:

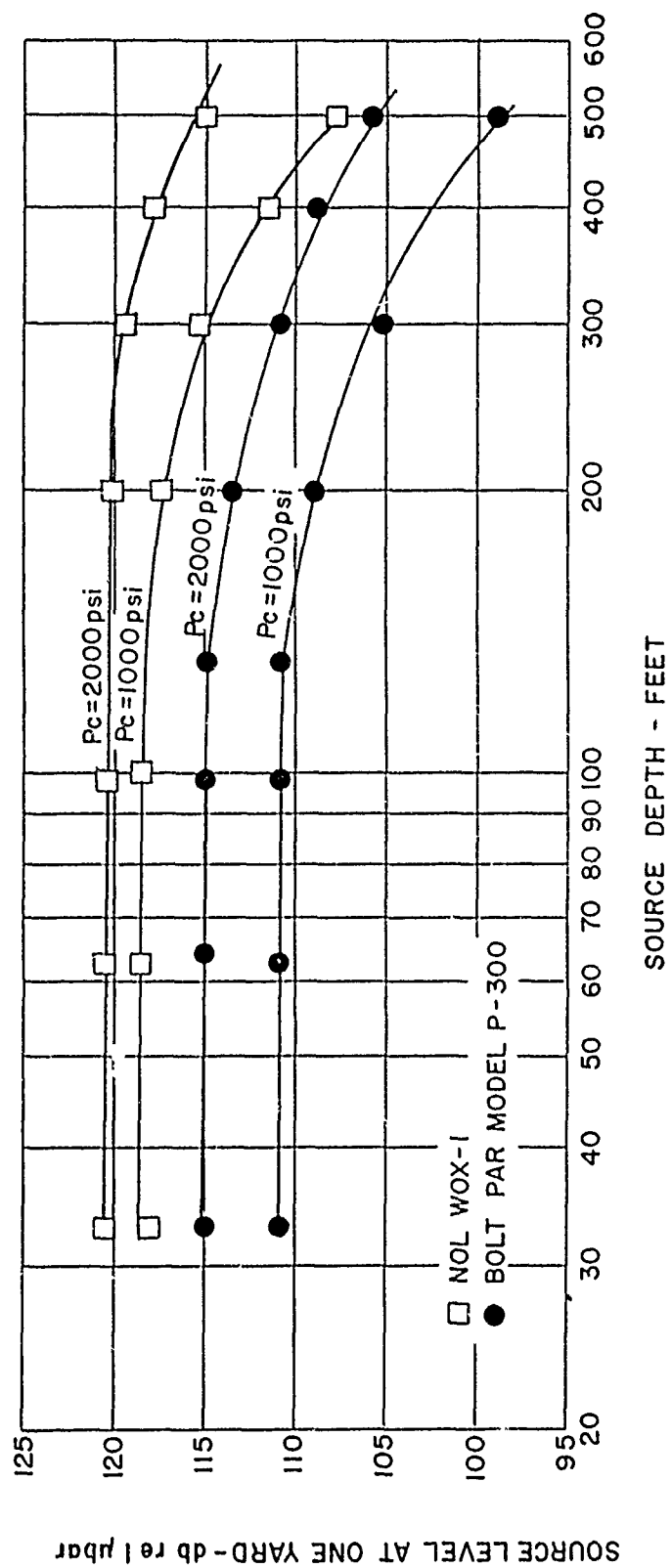| HYD #	CABLE LENGTH (MI.)
1	181.77
2	163.767
3	143.547
4	123.387
5	103.227
6	83.065

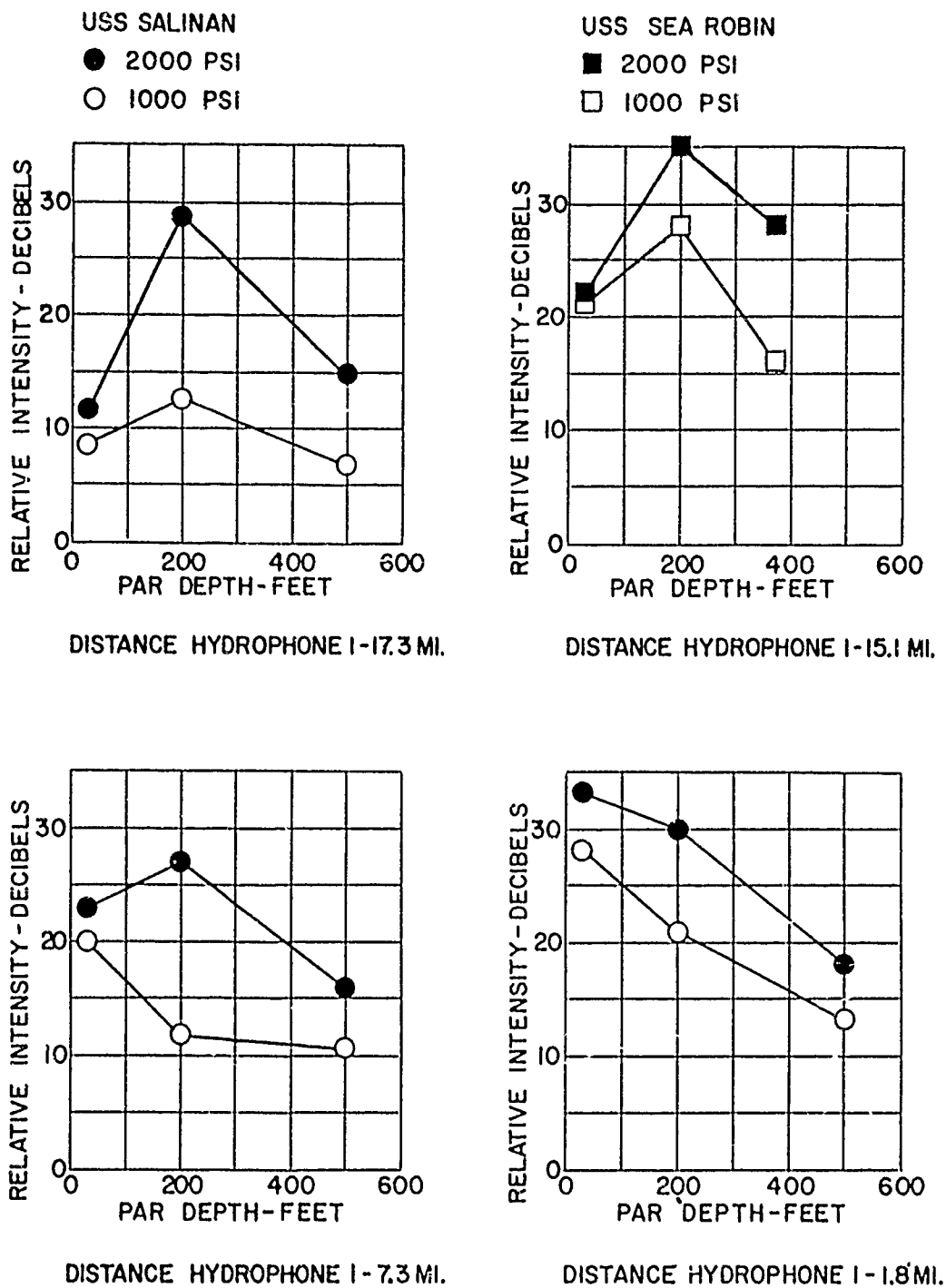Fig. 10. Output sound level content in 5 to 50 cps band vs source depth.

FIG. II. Relative intensity of PAR signal at mils hydrophone no. I vs depth of PAR.